$t\bar{t}W$ Modelling

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I. Introduction

The production of a top-quark pair in association with a W-boson ($t\bar{t}W$) is one of the rare and crucial processes in high-energy physics, offering a unique probe of the Standard Model (SM) and potential signals of new physics. This process occurs in proton-proton (pp) collisions at the Large Hadron Collider (LHC) and involves the simultaneous production of two top quarks and a W-boson, either through leading order or higher-order quantum effects.

Since the top quark decays before hadronizing, its properties (e.g., couplings to gauge bosons) can be studied directly. The presence of an additional W-boson to ttbar production affects the kinematics and the final state charge distribution, which allows the study of the charge asymmetry and spin correlation. Anomalies in the $t\bar{t}W$ cross-section and kinematics could hint at new physics and beyond the standard model (BSM) physics.

ATLAS and CMS in LHC have performed several measurements of $t\bar{t}W$ production [1- 4]. They focused on the determination of the cross section to be compared with the SM cross section. Since this process leads to signatures with two leptons having same signs or three leptons due to the decay of the top quarks and W, the study of multi-lepton final states becomes one of the major goals in ATLAS and CMS experiments. In addition, they developed various techniques using Machine learning to separate the background like the $t\bar{t}Z$, $t\bar{t}H$, and fake leptons from the main signal. Results from Run 2 showed improved precision measurements of the $t\bar{t}W$ process. They observed a cross section agreeing with the SM cross section but leaving room for further scrutiny in future high luminosity runs. It is worth noting that the ATLAS and CMS' results measured the differential cross-sections [5].

The theoretical predictions and modelling for $t\bar{t}W$ process become very important but challenging due to many complex reasons. First, the need for accurate and precise higher order QCD and electroweak (EW) corrections such as the Next-to-leading-order (NLO) and Next-Next-to-leading-order (NNLO) [6]. The $t\bar{t}W$ process pileups with other processes, therefore the interference effects must be handled carefully in the model. The process often involves additional jets from gluon splitting, final state and initial state radiation (FSR and ISR), which require advanced techniques for parton shower matching to get rid of the jet-multiplicity.

In this report, the $t\bar{t}W$ process have been studied using the RIVET toolkit *version 3* and *4*, and two Monto Carlo samples; one from SHERPA generator, and the other one from MadGraph5_aMC@NLO generator that implements the FxFx merging scheme. In the next section, the $t\bar{t}W$ modelling will be discussed. In the third section, the results will be represented and discussed. The last section will conclude with a simple illustration of the future perspectives on the $t\bar{t}W$ process and measurements.

II. $t\bar{t}W$ Modelling

II.1 $t\bar{t}W$ signal

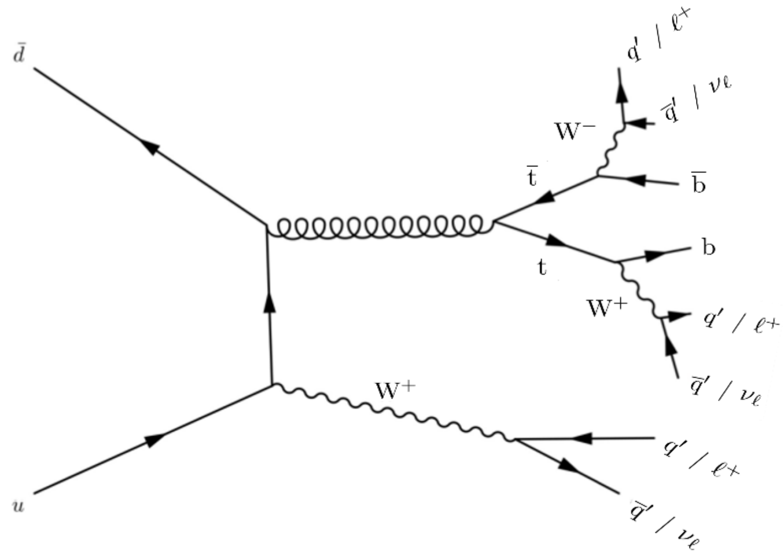

Figure 1. Feynman diagram for $t\bar{t}W$ process.

Figure 1 shows the $t\bar{t}W$ Feynman diagram. Top and anti-top quarks usually decay into b-quarks (b jets) and W-bosons. In association to this production, a third W-boson is produced. The W-boson always decays leptonically (electrons or muons with their associated neutrinos) or hadronically (quark and antiquark). In this study, two final-state selections have been studied; one is the production of 2 same-sign leptons from two W-bosons decay assuming that two W-bosons decayed leptonically and the third W-boson decayed hadronically, and the production of 3 leptons (from all the W-boson decays) assuming that all the W-bosons decayed leptonically.

II.2 Modelling input: data and simulated events samples

In this project, Monto Carlo (MC) record history of a limited number of events (2000) simulated within the ATLAS simulation framework under Run 3 data taking conditions have been used. $t\bar{t}W$ simulated events (mc23_13p6TeV.700997.Sh_2214_tt̄W_2Lfilter.evgen.EVNT.e8532.root) using SHERPA generator have been used in RIVET 3 model. Another $t\bar{t}W$ simulated events (EVNT.root) using MadGraph5_aMC@NLO generator.

RIVET routine (C++ code based) had been generated for the two MC samples. RIVET 3 have been used for the SHERPA sample and RIVET 4 have been used for the MadGraph5_aMC@NLO generator sample. The $t\bar{t}W$ MC simulated events must contain reconstructed electrons, muons, and one or two b-jets from the tt decay. An overlapping removal scheme is used to remove the interference between the photons and leptons from a cone of 0.1 radius. In the following section, details of the reconstruction scheme will be discussed deeply.

II.3 Event and jets reconstruction

The analysis begins by defining a common lepton selection criterion, requiring leptons to have an absolute pseudorapidity $|\eta| < 4.9$ and a transverse momentum $pT \geq 7.0$ GeV. This cut is then applied to construct dressed lepton collections. Specifically, dressed electrons and muons are identified by clustering photons within a cone of $\Delta R = 0.1$ around the bare leptons from the respective input collections, with photons being removed prior to the electron dressing process. These collections are declared as "dressedelectrons" and "dressedmuons". To isolate jets, a central final state ($|\eta| < 4.9$) is defined, from which the previously identified dressed leptons and any prompt invisible particles are vetoed. Anti-kT jets with a radius parameter $R = 0.4$ are then built from the remaining particles, including muons and invisible energy in the clustering process. Finally, two additional objects are declared: a collection of B and C hadrons with $|\eta| < 4.9$ and $pT > 5$ GeV, and the missing transverse momentum, which is calculated from all final state particles within $|\eta| < 4.9$.

To ensure the purity of the jet reconstruction, a multi-stage overlap removal procedure is applied. First, jets are cleaned of electron contamination by discarding any jet found within a radius of $\Delta R < 0.2$ of an electron. This process is repeated for a separate collection of softer jets (light quarks), which are cleaned against the same electron collection. Subsequently, the leptons are cleaned against these purified jets. Electrons and muons are removed if they are found within $\Delta R < 0.4$ of any jet in the "alljets" collection, yielding the final, non-overlapping electron and muon collections. Finally, these cleaned electron and muon collections are combined and sorted by transverse momentum to form a single lepton collection.

To implement the two selections; 2lSS and 3l, certain kinematic cuts have been applied. These kinematic cuts criteria will be explained in the following two subsections.

II.3.1 Two-lepton Same-Sign selection

In the kinematic cuts criteria, the events containing two leptons having same signs (2lSS) (total charge >0) is the main property for the 2lSS- $t\bar{t}W$ selection. For tracing the b-tagged jets from the tt system, the second kinematic cut applied that at least one b-jet contained from all the jets in the event. The leading and sub-leading leptons are constructed with pT >= 20 GeV. We considered the jet-merging problem in this selection, so we defined the pT of the leading additional jets that are not from the tt system and not from the $t\bar{t}W$ system. The light additional jets from the third W-boson are then traced by identifying their PID and their mother PID (which is 24, MC particle ID for W).

II.3.2 Three-leptons Selection

In the kinematic cuts criteria, the events with 3 leptons having a total charge of 1 are considered. These events must have at least two jets and one b-jet. Then, any additional jets not from the $t\bar{t}W$ system have been traced.

III. Results and Discussion

As a preliminary result, momentum distribution plots of the leading leptons in the MC SHERPA generator sample used for RIVET 3 and the MC MadGraph5_aMC@NLO generator sample used for RIVET 4 have been generated for 2lSS selection and represented graphically in Figure 2. Figure 3 shows the results from the 3 leptons in the final state selection. The results from RIVET 4 show that the momentum distribution of the leading leptons is less than the momentum of the leading leptons when using RIVET 3 for both selections. The leading leptons with lower momentums are much more in the MC simulated events compared to higher momentum leading leptons in both selections.

a. b.

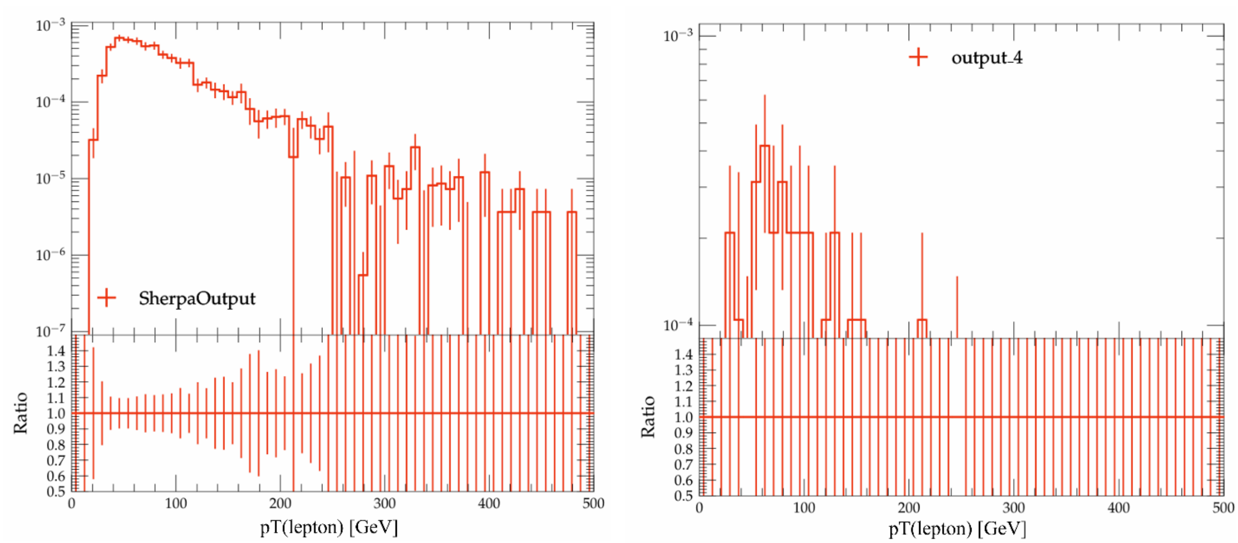

Figure 2. Momentum distributions for the leading leptons in the two leptons same-signs selection in the final state. (a) Results using MC SHERPA sample, and (b) using MC MadGraph5_aMC@NLO sample.

a. b.

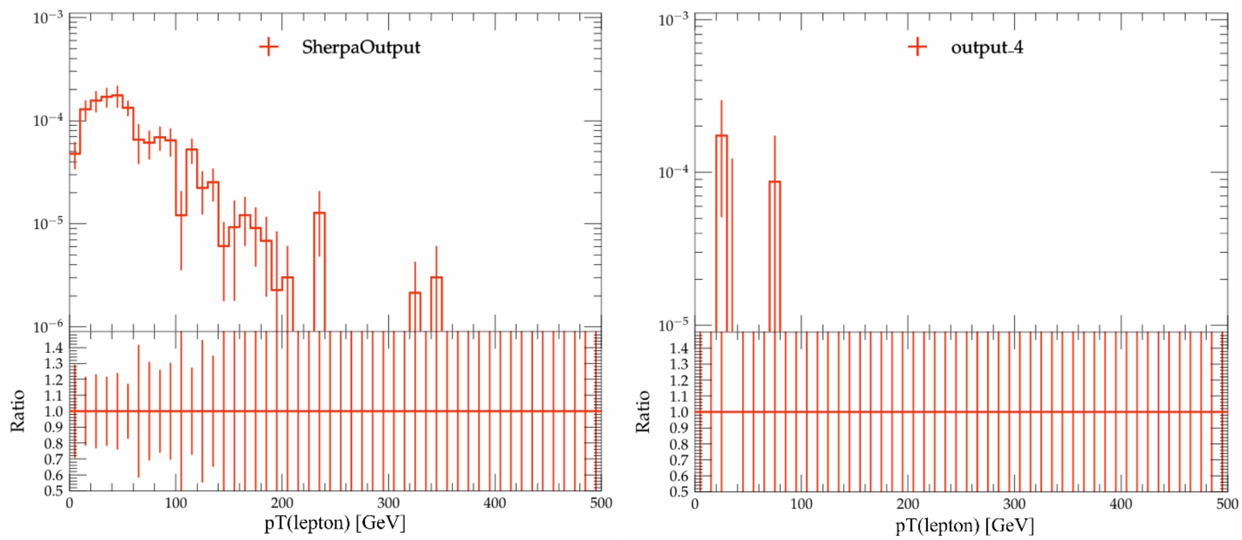

Figure 3. Momentum distributions for the leading leptons in the three leptons selection in the final state. (a) Results using MC SHERPA sample, and (b) using MC MadGraph5_aMC@NLO sample.

The additional jets in the two selections have been studied and analyzed in order to validate the jet multiplicity which have been implemented in MadGraph5_aMC@NLO generator. A container called “additional_jets” in the code is added to separate any additional jets in any ttW process from “all_jets” container. The “additional_jets” container can contain b-jets or light jets. In the 2lSS selection, the additional jets contain the light jets which can be from the third W-boson decay, or/and gluon splitting. However, the additional jets in the three leptons selection are not from the ttW system. From this, the jet-merging fix have been validated for the MC MadGraph5_aMC@NLO sample.

Figures 4 and 5 show the momentum distributions of the leading additional jets in both MC samples for both selections. It can be observed that the momentum is distributed largely in both selections when using RIVET 3. Whereas RIVET 4 results showed a very shaped and selective momentums have only appeared for the leading additional jets. This indicates that the MC MadGraph5_aMC@NLO sample can get rid of the jet multiplicity issue. It is worth noting that the three leptons selection in the final state results in Figure 5 represents a very low number of additional jets since all the W-bosons are assumed to be decayed leptonically.

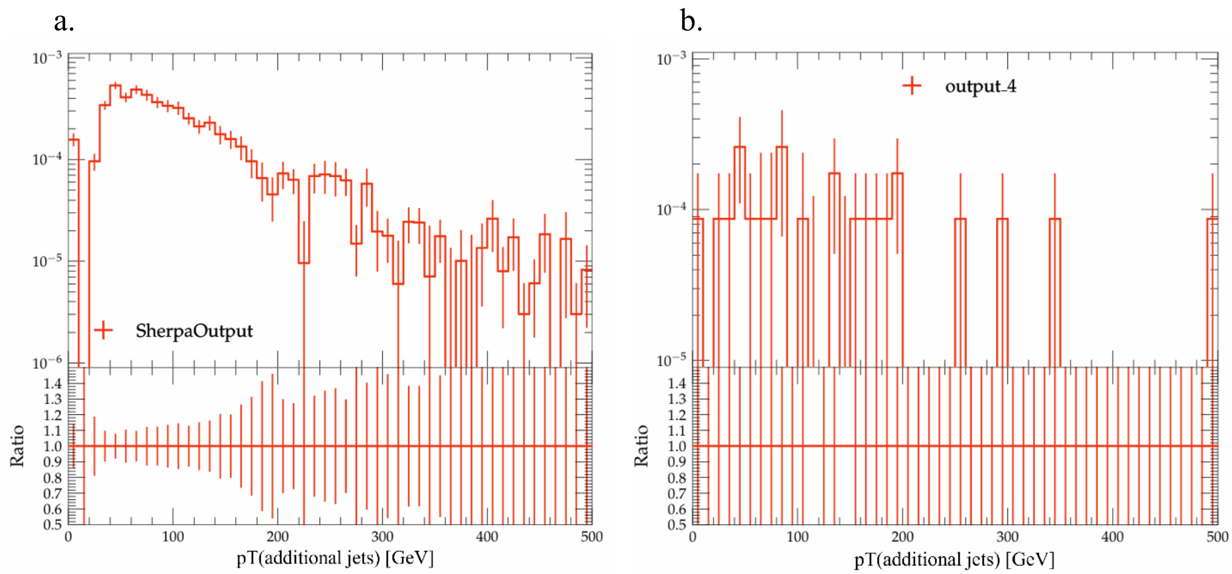

Figure 4. Momentum distributions for the leading additional jets in the two leptons having same signs selection in the final state. (a) Results using MC SHERPA sample, and (b) using MC MadGraph5_aMC@NLO sample.

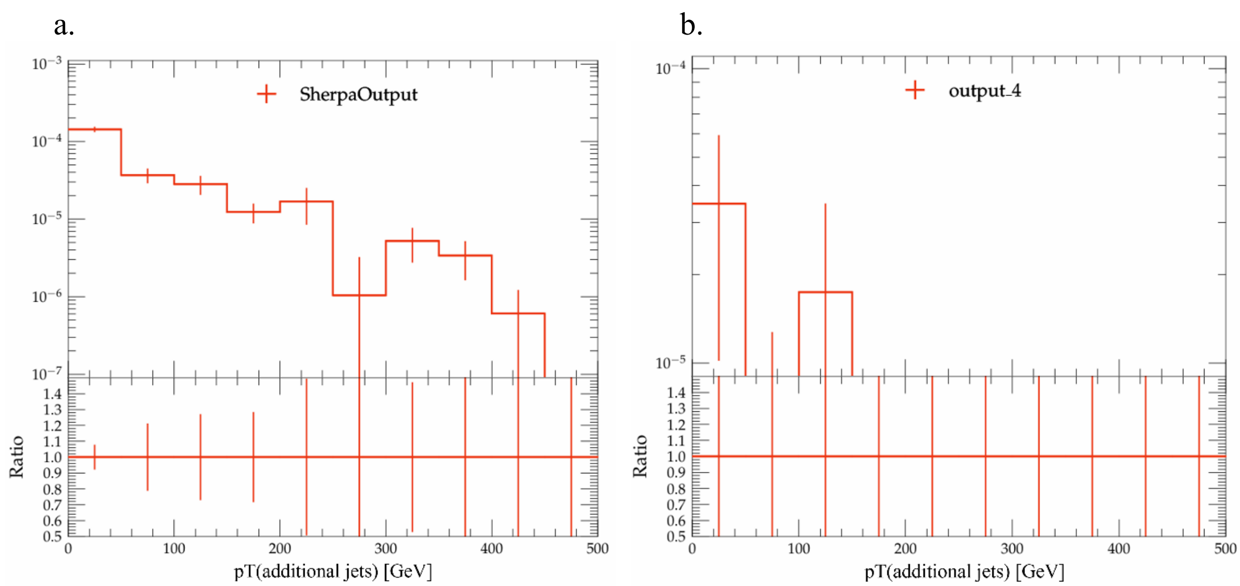

Figure 5. Momentum distributions for the leading additional jets in the three leptons selection in the final state. (a) Results using MC SHERPA sample, and (b) using MC MadGraph5_aMC@NLO sample.

Conclusion

In this report, two different routines have been produced and modified in order to analyze and study two selections of the $t\bar{t}W$ final states particles. The selections were the production of two leptons coming from two W-bosons having same signs and the leptonic decay of the all the W-bosons in the process. To achieve accurate analysis, RIVET 3 and 4 routines were used for implementing the two selections and producing the momentum plots. The jet-merging fix have been applied and implemented in the MadGraph5_aMC@NLO sample. Therefore, this fix has been validated by comparing the results from the two samples. As a result, RIVET 4 routine plots show that the multiplicity of the jets is reduced.

References

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